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Arya, F., Hyde, T., Henshall, P., Eames, P., Moss, R., Shire, S., & Zacharopoulos, A. (Accepted/In press). Thermal Analysis of Flat Evacuated Glass Enclosure for Building Integrated Solar Applications. In *Unknown Host Publication* (pp. 256-263). World Economic Forum. <http://conferencecentre.org/publication/10004587>

[Link to publication record in Ulster University Research Portal](#)

**Published in:**  
Unknown Host Publication

**Publication Status:**  
Accepted/In press: 15/09/2015

**Document Version**  
Author Accepted version

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# Thermal Analysis of Flat Evacuated Glass Enclosure for Building Integrated Solar Applications

Farid Arya<sup>1</sup>, Trevor Hyde<sup>1</sup>, Paul Henshall<sup>2</sup>, Phillip Eames<sup>2</sup>, Roger Moss<sup>3</sup>, Stan Shire<sup>3</sup>,

Aggelos Zacharopoulos<sup>1</sup>

<sup>1</sup>Center for Sustainable Technologies, Ulster University, BT37 0QB, UK

[t.hyde@ulster.ac.uk](mailto:t.hyde@ulster.ac.uk), tel. +44 28 90368235

<sup>2</sup>Centre for Renewable Energy Systems Technology, Loughborough University, UK,

[el-enquiries@lboro.ac.uk](mailto:el-enquiries@lboro.ac.uk)

<sup>3</sup>School of Engineering, University of Warwick, UK, [engineering@warwick.ac.uk](mailto:engineering@warwick.ac.uk)

## Abstract

In this work a flat evacuated glass enclosure is designed and fabricated and its thermal performance characterized for solar thermal applications. To investigate the effect of the thermal insulation provided by the high vacuum pressure in the enclosure, the heat transmission of the enclosure is determined under both atmospheric and vacuum pressures. The flat evacuated enclosure consists of two glass panes hermetically sealed around their periphery to a stainless steel spacer creating a cavity between the glass panes 15mm wide. An array of stainless steel support spacers are set between the glass panes to prevent the panes from collapsing under the influence of atmospheric pressure.

A simple solar absorber is integrated into the enclosure and a novel co-centric port is designed for thermal fluid transfer through the edge spacer to the absorber. The assembly is tested under a solar simulator, and using infrared thermography techniques and thermocouples attached to the enclosure its thermal response is analysed. Results show that the greatest heat loss occurs near the support spacers on the glass surface, and near the inlet and outlet ports at the edge spacer.

Key words: Evacuated Glass Enclosure, Vacuum Insulation, Evacuated Co-centric tube, Solar thermal, Solar simulator, Infrared Thermography

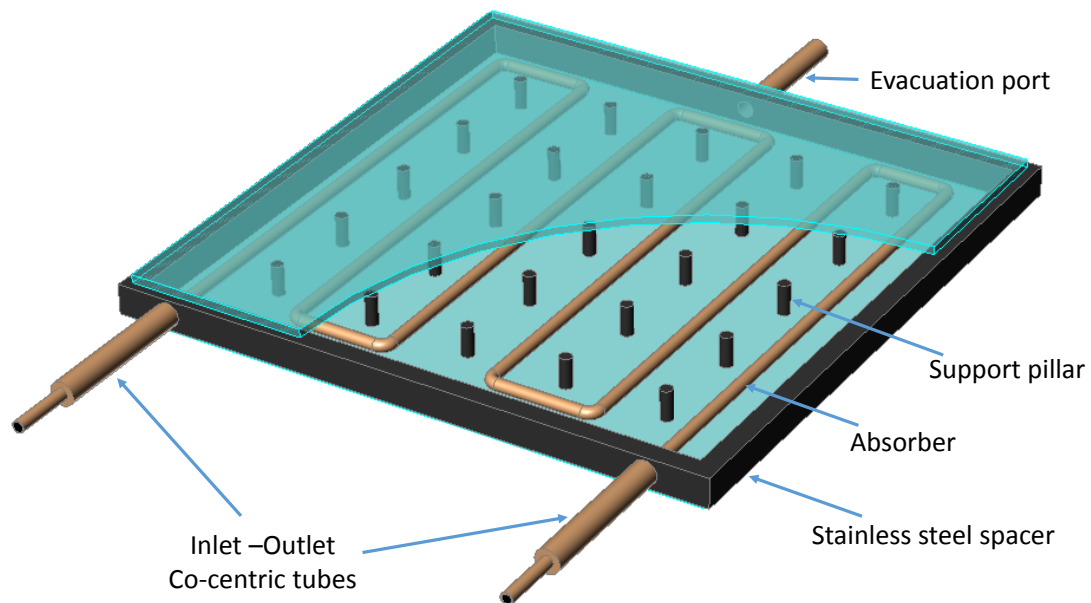
## 1. Introduction

Creating a vacuum space around a flat solar absorber thereby taking advantage of its high thermal insulation properties has been investigated by many researchers [1, 2, 3]. There are a number of challenges in the fabrication of these kinds of solar collectors: the first challenge is to create a hermetic seal around the periphery of the glass panes which is strong enough to withstand all stresses caused by atmospheric pressure and thermal expansion/contraction over its life time. The second challenge is to maintain the separation of the glass panes under the influence of atmospheric pressure. Finally, a careful design of inlet and outlet port is required which provide a particularly realizable minimum heat loss.

In previous work, prototypes of slim flat vacuum panels 400mm by 400mm suitable for use in solar thermal collectors were fabricated and their thermal performance characterized using a guarded hot box calorimeter. In these experiments a U-value of  $0.86\text{Wm}^{-2}\text{K}^{-1}$  was achieved [4]. The wide vacuum space between the panes enables the integration of a similarly wide solar absorber. The vacuum provides a high level of thermal insulation around the solar absorber, reducing heat losses from the absorber by conduction and convection thereby increasing the efficiency of the solar

collector. However, in this work the main focus is the design of the inlet and outlet ports for the panel. A simple absorber was integrated in the panel to investigate the potential challenges in achieving this. The inlet and outlet designs will be used in future work which includes the integration of a high efficiency solar absorber in the panel. The current absorber has a very small surface area and its efficiency is expected to be low. The simple collector is tested under a solar simulator available at Ulster University.

A schematic diagram of the flat vacuum enclosure and absorber is shown in Figure 1. The collector consists of a simple solar absorber which uses co-centric inlet and outlet ports through the edge seal spacers. Two glass panes are hermetically sealed around their periphery to the stainless steel spacer creating a cavity between the glass panes which is to be evacuated. By creating a high vacuum in the cavity the inlet and outlet tubes are also thermally insulated, as a result heat loss from them to the edge spacer is minimised.



*Figure 1: A schematic diagram of the evacuated glass enclosure with the integrated solar absorber.*

Using ultrasonic soldering techniques, an alloy is used to create a hermetic seal at temperatures of approximately 220°C. Hard low emittance coatings are used on the internal glass surfaces to minimize radiative heat losses. Arrays of stainless steel support pillars are set between the glass panes to prevent the panes from collapsing under the influence of atmospheric pressure. The sealing process is undertaken in a bake out oven. After the formation of the edge seal, the evacuation of the panel is undertaken.

Heat transfer between the absorber and the glass panes can occur due to radiation between the absorber and the internal surfaces of the glass panes, and thermal conduction and convection through residual gas in the evacuated gap. The only contact points between the absorber and the enclosure in this solar collector are the joining points in the co-centric tubes as illustrated Figure 2. These parts of the tubes can be easily insulated using conventional insulation materials such as glass wools. Since the absorber is light and rigid, by soldering the co-centric tubes to the spacer the absorber is fixed and held between the two glass panes supporting its own weight. In future work where a high efficiency flat absorber is integrated into the vacuum enclosure it will be necessary to provide a number of brackets in the enclosure to support the absorber.

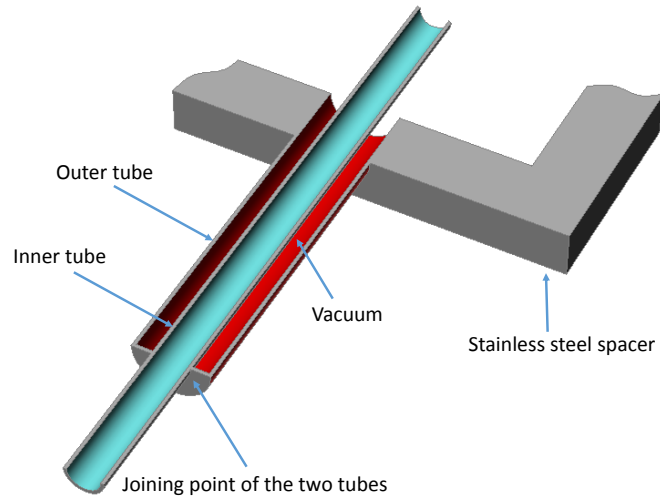


Figure 2: Schematic diagram of a co-centric tube.

To investigate the effectiveness of the vacuum space in minimizing heat loss from the absorber an infrared thermography technique is used. By passing hot water through the absorber a temperature difference is created between the absorber and the vacuum enclosure. The heat flux through any contact point between the absorber and the vacuum enclosure must be detectable using thermography techniques otherwise it would indicate that the heat flow contributed by the residual gas in the cavity is comparable with the heat flow through those contact points.

## 2. Fabrication Process:

The first step in the fabrication of the flat solar collector is to fabricate the absorber. The absorber is made of a 2.1m long stainless steel tube with outside diameter (OD) of 6mm, and inside diameter (ID) of 5mm. To minimise the heat loss from the absorber to the stainless steel spacer the inlet and outlet tubes are chosen to be co-centric. The co-centric tube consists of an inner tube (OD: 6mm, ID: 5mm) and an outer tube (OD: 12mm, ID: 10mm) hermetically sealed to each other as well as to the spacer using silver soldering techniques. A stainless steel tube is also soldered to the spacer for evacuation purposes. After the soldering process is completed the spacer and the tubes are polished using a fine emery paper and cleaned using diluted Hydrochloric acid (33%) to remove any residues left from the soldering process. The absorber and the spacer are shown in Figure 3, all components are made of stainless steel (304L grade).

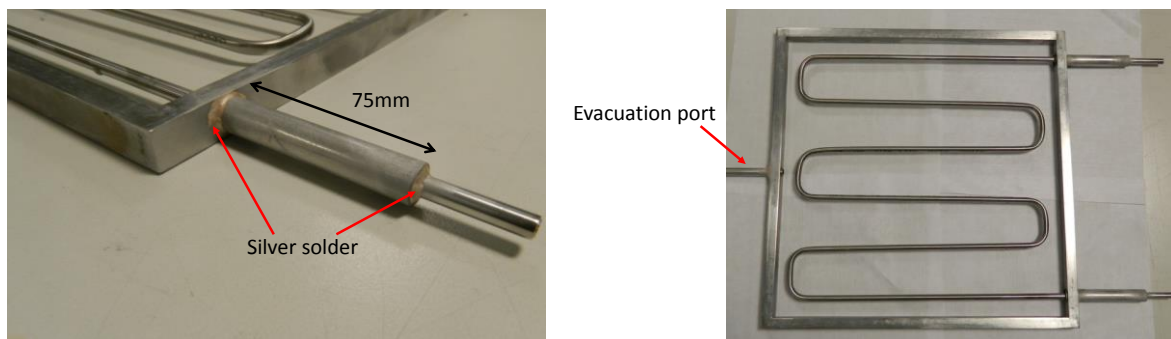


Figure 3: The spacer and absorber.

The second step in the fabrication of the flat solar collector is to form a leak-free seal between two glass panes and the spacer around their perimeters. This is accomplished by bonding two glass panes to the spacer (15mm thick and 10mm wide) with an alloy seal/Cerasolzer 217 using an ultrasonic soldering technique. This technique enables the solar collector to be produced in a bake-out oven at a temperature of about 220°C. Using the ultrasonic soldering technique to create hermetic seals in ultra-high vacuum applications is described in detail elsewhere [5]. Both glass panes are 4mm thick K-glass, sized 0.3m by 0.3m, with low-e coatings (emittance of 0.16) on the glass surfaces facing the vacuum gap.

The separation of the panes which would otherwise touch under the influence of atmospheric pressure is maintained by an array of stainless steel (grade 304L) support pillars. The pillars are 15.2mm high and 6mm in diameter and spaced at 50mm intervals on a regular square Cartesian grid.

After the edge seal formation and subsequent cool down, the collector is connected to a turbo molecular vacuum pump via the evacuation port. A completed prototype of a flat vacuum solar collector is shown in Figure 4.



*Figure 4: Fabricated flat vacuum solar collector.*

### **3. Thermal Analysis**

In the flat vacuum solar collector shown in Figure 4 the vacuum provides a high level of thermal insulation around the solar absorber which reduces heat loss from the absorber by conduction and convection. However, heat loss can still occur due to radiation from the absorber, and also through the contact points between the enclosure and the absorber. Using low emittance coatings on the internal surfaces of the glass panes minimises radiative heat losses. However, there is still a point in the co-centric tube where the two components are in contact, shown in Figure 2, this also contributes to heat loss from the absorber. To examine the effectiveness of the vacuum insulation in minimising the heat loss from the absorber an experiment is set up in which a temperature difference is created between the absorber and the enclosure by passing hot water through the absorber. A Julabo is used to provide hot water with a constant temperature of 82°C. A number of thermocouples (K-type) are attached to different points of the enclosure. Two thermocouples are also used to measure the inlet and outlet water temperatures. The thermocouple locations and steady state temperature results, with and without vacuum, are shown in Figure 5.

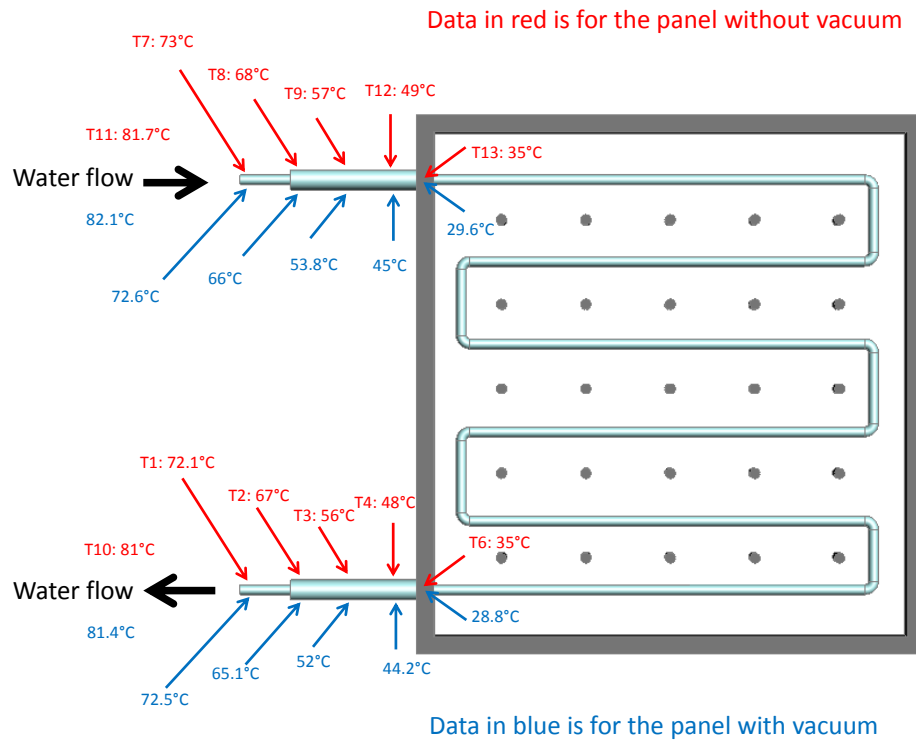


Figure 5: The thermocouple locations and recorded temperature.

To investigate the effectiveness of the vacuum space in minimizing heat loss from the absorber an infrared thermography technique is used. By running hot water (82°C) through the absorber a temperature difference is created between the absorber and the vacuum enclosure while the ambient temperature is 23°C. The heat flux through any contact points between the absorber and the vacuum enclosure is detected as shown in Figure 6. In this experiment an infrared camera (FLIR: B640) is used to take IR images. Figure 6 clearly demonstrates the difference between an evacuated and non-evacuated collector. Both images are taken 30 minutes after the hot water starts circulating. The collector with no vacuum (Figure 6a) has greater heat loss in comparison to the other collector (Figure 6b) in which there is a high vacuum ( $7.2 \times 10^{-5}$  mbar). The co-centric inlet and outlet tubes exhibit excellent insulation in the evacuated collector whilst their performance is poor in non-evacuated collectors.

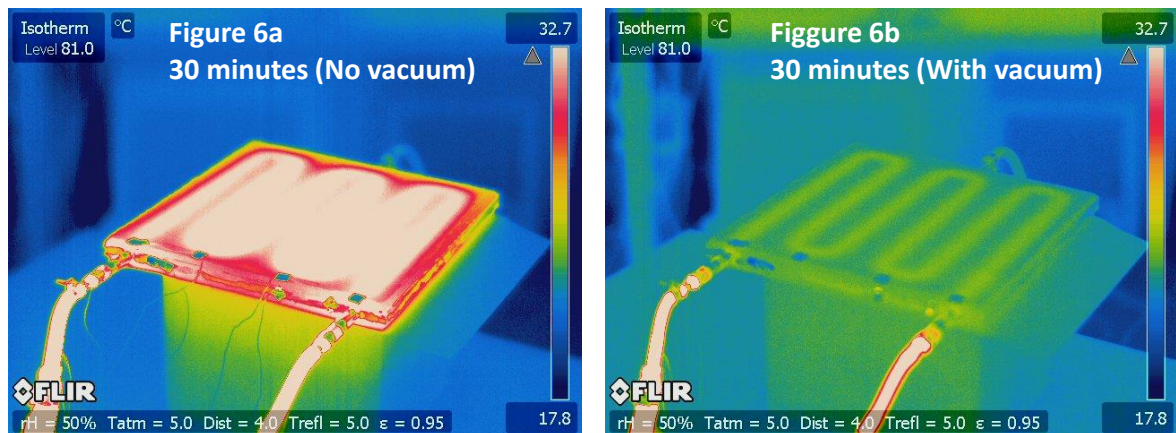


Figure 6: Comparison between evacuated and not-evacuated solar collector. Both pictures are taken in 30 minutes of running hot water.



Figure 7 demonstrates that heat transfer from the absorber to the enclosure is very slow if a high vacuum is created in the enclosure. The images in Figure 7 are taken in one hour intervals from each other.

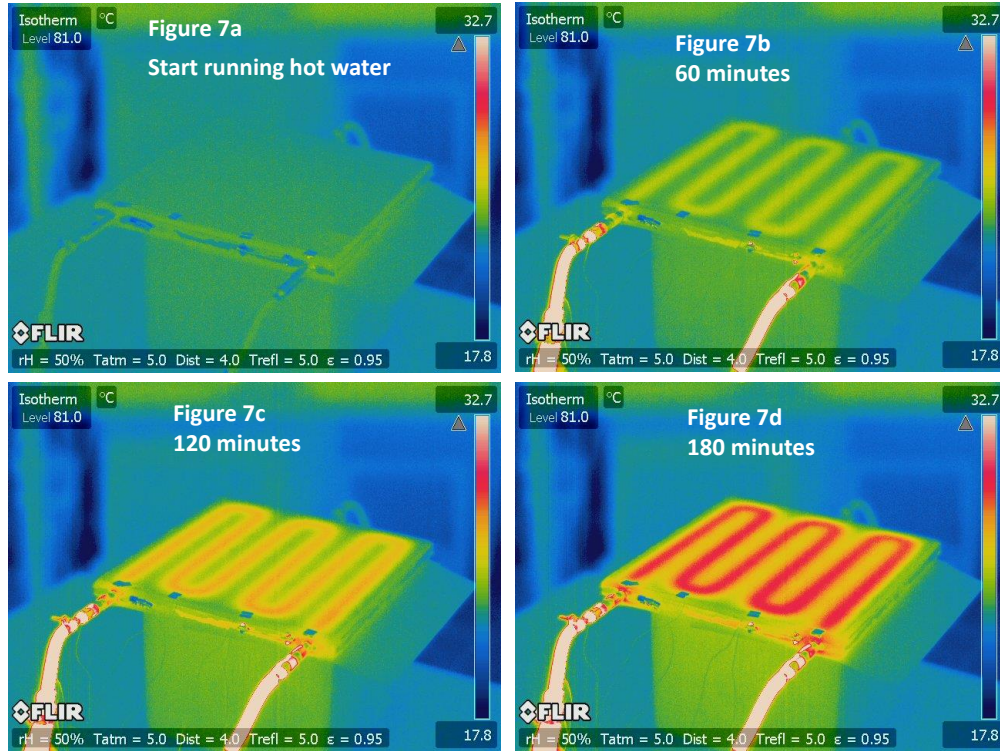


Figure 7: Infrared images taken in one hour intervals. The vacuum pressure is  $7.2 \times 10^{-5}$  mbar.

Figure 8 shows an IR image taken 5 hours after the hot water (82°C) starts running through the absorber. At that point the infrared camera detects an increased temperature above the support pillars. Since there is no contact between the support pillars and the absorber, this may result from radiation exchange between the absorber and the pillars.

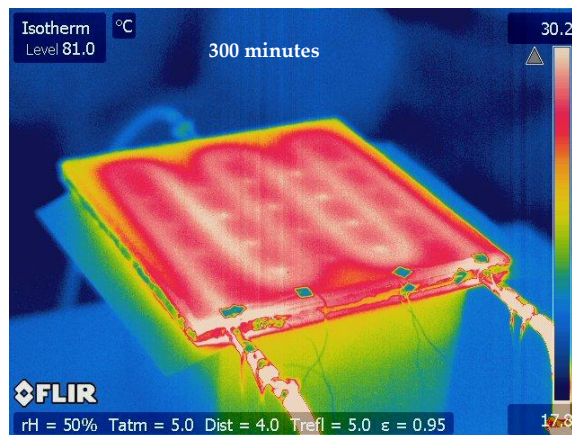


Figure 8: IR image is taken 5 hours after the hot water (82°C) starts running through the collector. The support pillars exhibit temperature variations.

To further investigate the temperature variation on the glass surface a number of thermocouples are attached to the top glass pane as illustrated in Figure 9. Internal vacuum pressure is  $7.2 \times 10^{-5}$  mbar. Results also presented in Figure 9 clearly demonstrate that the temperature of the glass cover above the support pillars is higher than that at locations remote from them. Furthermore, as expected from the IR images, the temperature of the glass cover is the largest above the absorber tubes.

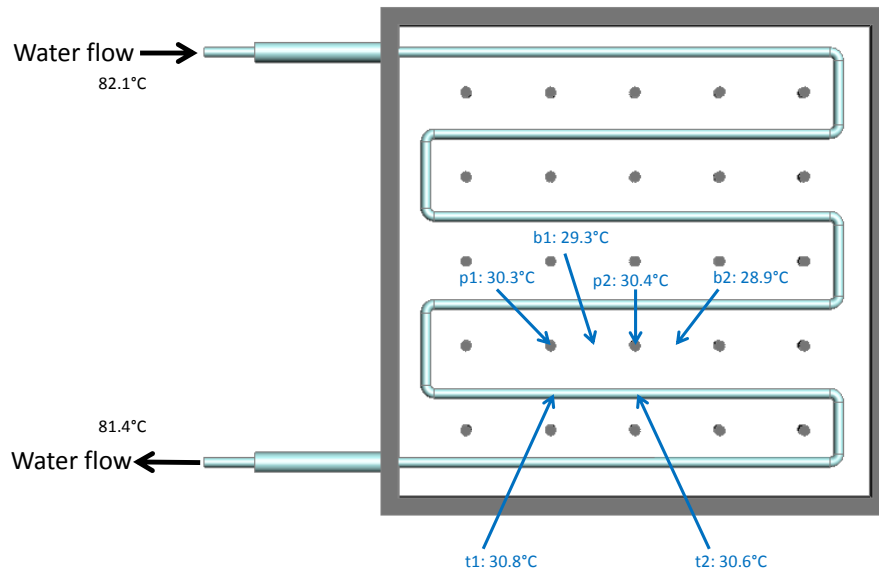


Figure 9: Thermocouple locations and recorded temperatures.

Since the absorber does not have a large surface area and its surface is not selectively coated the collector cannot operate with high efficiency, however, it was also tested under a solar simulator. The distance between the collector and the solar simulator is 2m and the light intensity on the surface of the collector is  $770 \text{ W/m}^2$ . All technical details related to the solar simulator are given elsewhere [6].

The flat vacuum collector is set under the solar simulator and a water supply is provided. The test is undertaken with a mass flow rate of  $\dot{m} = 0.011 \left( \frac{\text{kg}}{\text{s}} \right)$ .

The solar simulator and the water flow are maintained for two hours. At this point the temperature difference between inlet and outlet water is measured, while the ambient temperature is  $23^\circ\text{C}$  and the inlet water is at  $16^\circ\text{C}$ . The temperature difference is  $\Delta T = 1^\circ\text{C}$ .

#### 4. Summary and Conclusion:

A flat vacuum collector prototype was fabricated from two glass panes, a simple absorber and a stainless steel spacer using a low temperature edge sealing process. Co-centric tubes were designed and used as inlet and outlet ports to the collector. Using Cerasolzer 217 as a sealant and an ultrasonic soldering technique the edge seal between the glass panes and the stainless steel spacer was formed in a bake-out oven. The spacer, the support pillars and the absorber were made of stainless steel (304L grade).

During evacuation atmospheric pressure induces large stresses across the vacuum collector particularly in the region of the edge seal and the support pillars. The edge seal was hermetic and also strong enough to withstand stresses caused by atmospheric pressure and thermal expansion/contraction. Further work is needed in order to evaluate the durability of the edge seal over time. However, during the evacuation and thermal characterization of the vacuum collector



the edge seal did not fail. Metal seals usually deteriorate due to moisture ingress [7]; in the long term the Cerasolzer edge seal should be augmented with an epoxy resin to provide protection against moisture ingress and to provide additional structural rigidity.

Infrared thermography and temperature measurements proved that the co-centric tubes minimised heat loss from the inlet and outlet ports to the edge spacer. For further improvement it is also possible to insulate the co-centric tubes by conventional insulations. A similar design, therefore, will be used in the flat vacuum collectors fabricated for future experiments. Thermal characterisation of the vacuum collector under both atmospheric and vacuum pressures demonstrated that the vacuum around the absorber reduced the heat loss from the absorber to the enclosure via the suppression of gaseous convection and conduction.

The test demonstrated that despite the fact that there was no contact between the absorber and the support pillars, there was some level of heat loss from the absorber to the support pillars via radiation. This could prove problematic if the absorber is wider and the distance between the pillars and the absorber is small. This heat loss could be reduced by using ceramic or glass support pillars instead of stainless steel.

Testing the flat vacuum collector under a solar simulator demonstrated poor operational efficiency. This was expected because the absorber had a very small surface area and it did not have any high performance coating. If a wide solar absorber with high performance coatings is incorporated in the vacuum enclosure an increase in the efficiency of the solar collector would be expected.

This research presents an accurate and reproducible fabrication method for flat vacuum collectors which have the potential to be exploited in a flat vacuum solar collector production line.

## 5. Acknowledgement

The support from the UK Engineering and Physical Sciences Research Council (EPSRC) through EP/K010107/1 is gratefully acknowledged.

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